RADIATIVE CAPTURE REACTIONS AT INTERMEDIATE ENERGIES

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Following the observation by our group[1] of strong radiative capture transitions to highly excited states in light nuclei, we have continued to investigate the features of these reactions in the 24-80 MeV range. Some of the early qualitative ideas generated by our initial experiments[2,3] have been put on a firmer, more quantitative footing during the past year through both our own efforts[4,5] and the theoretical and experimental work of other groups[6-8]. The most significant results at this point are the following: a) confirmation of the second-harmonic giant resonance; b) evidence for a third-harmonic resonance; and c) understanding of the detailed similarities between pairs of "identical" single-particle transitions in neighboring closed-subshell and closed-subshell plus one proton nuclei. These results will be described in the next few paragraphs. Previously reported suggestions of the (p,γ) reaction's sensitivity to simple single-particle final states[2,3,9] continue to be a useful guide in interpreting our observations.

Our search for a giant resonance in ^{12}C built on the 1$\hbar\omega$ 1p-1h excited states near 19 MeV had resulted in the discovery of a broad resonance in the ^{11}B(p,γ_{19})^{12}C* cross section at an excitation in ^{12}C of about 42 MeV, i.e., just about the same energy above its final state as the ordinary GDR is above the ground state (see Fig. 1). Attempts were made to understand this result in the context of direct-capture models[6] but neither the energy dependence nor the magnitude of

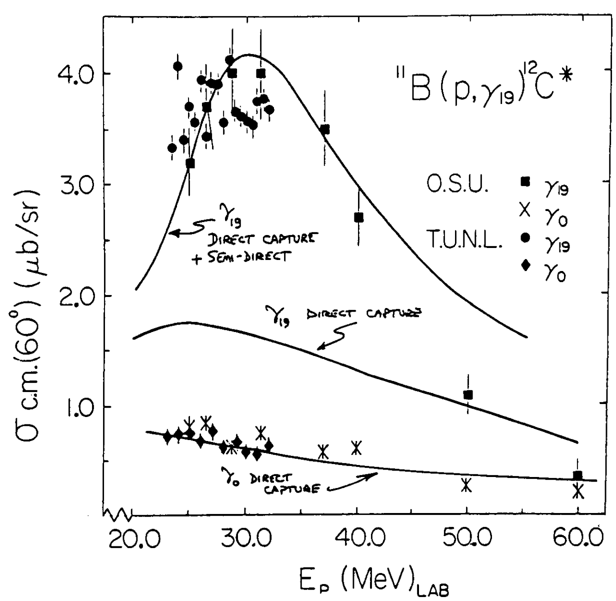

Figure 1. Cross sections for proton capture to the ground state (γ_0) and 19-MeV region (γ_{19}) of ^{12}C. A direct capture calculation fits γ_0, but fails to account for all the γ_{19} strength; addition of a semi-direct contribution at E_p=28.4 MeV is indicated.

the experimental cross section, as further verified in a collaboration with the TUNL group,[4] could be accounted for if only a direct mechanism were operating. Londergan and Ludeking[6] showed that a more reasonable description of the data did result, however, from the addition of a semi-direct resonance term.

Preliminary data by Dowell et al.,[7] in ^{28}Si, and Anghinolfi et al.,[8] in ^{12}C, indicate that there are giant resonances built on essentially every state in these nuclei. This scheme is illustrated in Fig. 2. This observation would appear to remove any remaining

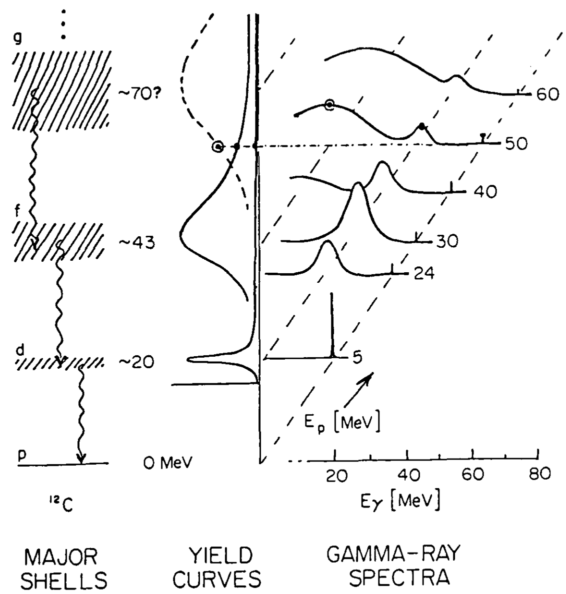

Figure 2. Theoretical gamma-ray spectra resulting from a sequence of E1 giant resonances. The intensities of various features of the E_p=50 MeV spectrum are highlighted to show how they are related to the assumed yield curves.

doubts on the resonant nature of the γ_{19} cross section.

In $^{11}B(p,\gamma)^{12}C$ spectra taken at higher energies,[10] capture strength to final states in the vicinity of the second harmonic resonance (~42 MeV) has also been seen. The yield curve for these capture transitions has been studied from E_p=45 MeV to 70 MeV [$E_x(^{12}C)$=56 to 80 MeV]; it shows a very broad peak centered at about E_x=65 MeV. The data are being carefully analyzed to determine the cross section for what appears to be a giant resonance on the $2\hbar\omega$ "second harmonic," which would then likely be a $3\hbar\omega$ excitation, or "third harmonic".[4]

Arnold[3] originally pointed out the similarity in the $^{11}B(p,\gamma)^{12}C$ and $^{12}C(p,\gamma)^{13}N$ spectra from our early measurements, noting that the major transitions in both cases were to good single-particle states (1p-1h for ^{12}C, 1p for ^{13}N) with the same orbit for the captured proton. Treating the target nucleus as a spectator in the reaction, which, in the ^{12}C case only introduces small splittings of the final states due to coupling with the $p_{3/2}$ hole, explains the similarities in spectra and suggests more detailed similarities in such reaction pairs. We earlier reported[2,11] on spectrum similarities on other pairs of reactions [$^{15}N(p,\gamma)^{16}O$ and $^{16}O(p,\gamma)^{17}F$; $^{27}Al(p,\gamma)^{28}Si$ and $^{28}Si(p,\gamma)^{29}P$]; more recently, we returned to the ^{12}C-^{13}N pair, making quantitative comparisons between corresponding transitions in the two nuclei. We looked at two such transition pairs: a) captures to the 19 MeV (4^-) state of ^{12}C and the 3.55 MeV ($5/2^+$) state of ^{13}N, both with $d_{5/2}$ final proton orbits; and b) captures to the 4.4 MeV (2^+) state of ^{12}C and the $1/2^-$ ground state of ^{13}N, both with $p_{1/2}$ final orbits. The shapes of the angular distributions and the analyzing powers for each member of the corresponding pairs are identical, within experimental uncertainties (see Fig. 3). Further, the ratios of the cross sections for members of these transition pairs are predictable from a knowledge of the spectroscopic factors of the final states involved. This latter result, which could be derived from a simple direct-capture reaction picture, persists over a wide range of energies, including resonance regions where direct capture is clearly of secondary importance. A "generalized direct--semi-direct" picture which retains the ability to describe our (quantititive) comparisons, but is much less restrictive in its assumptions than the conventional direct and semi-direct models, has been developed; this picture, and the experimental comparisons themselves are described in a forthcoming publication.[5]

Work is continuing on experiments to further generalize these results by looking at additional nuclei. Measurements at higher energies, which can be uniquely performed at IUCF, are also being pursued, as are more complex capture reactions (deuteron capture, ^{3}He capture, etc.), which should lead to a better

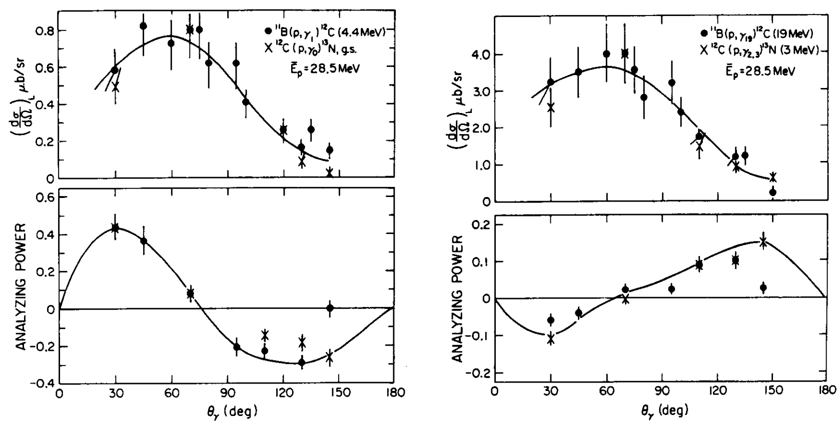

Figure 3. Comparisons of angular distributions and analyzing powers for corresponding transitions in $^{11}B(p,\gamma)^{12}C$ and $^{12}C(p,\gamma)^{13}N$. The cross sections are absolute for captures into ^{12}C, while those into ^{13}N are normalized at $\theta\gamma$=70° for direct comparison of shapes. On the left are the comparisons for capture of a final state $p_{3/2}$ proton; on the right, those for $d_{5/2}$.

understanding of both the nature of the final states involved in the capture reactions and the details of the capture mechanism. These new studies will be aided by improvements in our detector system, especially the recent installation of a new Bicron 10" × 12" NaI(Tℓ) crystal, which has produced an energy resolution of 2.1% at E_γ=40 MeV and a time-of-flight resolution better than 2 nsec.

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